

# Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry

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[1] RADARSAT data from the 1997 Antarctic Mapping Mission are used interferometrically to solve for the 3-dimensional surface ice motion in the interior of the West Antarctic Ice Sheet (WAIS). An area of  $\sim 125 \text{ km}^2$  in a tributary of the Kamb Ice Stream slumped vertically downwards by up to  $\sim 50 \text{ cm}$  between September 26 and October 18, 1997. Areas in the Bindshadler Ice Stream also exhibited comparable upward and downward surface displacements. As the uplift and subsidence features correspond to sites at which the basal water apparently experiences a hydraulic potential well, we suggest transient movement of pockets of subglacial water as the most likely cause for the vertical surface displacements. These results, and related lidar observations, imply that imaging the change in ice surface elevation can help reveal the key role of water in the difficult-to-observe subglacial environment, and its important influence on ice dynamics.

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## 1. Introduction

[2] It is important to understand current and past changes in ice flow from the West Antarctic Ice Sheet (WAIS) in order to constrain estimates of the future contribution of West Antarctica to global sea level rise [Alley and Bindshadler, 2001]. The Siple Coast ice streams in particular have exhibited very large flow fluctuations [Fahnestock *et al.*, 2000], including stagnation of Kamb Ice Stream (KIS, previously Ice Stream C) around 150 years ago [Retzlaff and Bentley, 1993], and the current slowdown of Whillans Ice Stream (WIS, previously Ice Stream B) [Joughin *et al.*, 2002]. Although unproven, it is widely accepted that the KIS stagnation is associated with a decrease in availability of subglacial water [Alley *et al.*,

1994]. Consequently, understanding changes in the WAIS mass balance and predicting its future contribution to sea level rise depend to a large extent on improved knowledge of the basal water system [Bougamont *et al.*, 2004]. Here we present evidence for surface height changes suggesting that subglacial water drainage beneath some ice streams and tributaries is not always continuous, but can include a transient or episodic component. Our results are based mainly on analysis of RADARSAT interferometric (InSAR) data.

[3] Survey measurements on mountain glaciers have shown that water storage and release can cause ice surface elevation changes [Iken *et al.*, 1983]. Also, Fatland and Lingle [2002] observed concentric phase patterns or 'bulls eyes' with ERS 1- and 3-day InSAR pairs from the 1993–95 surge of the Bering Glacier in Alaska, and suggested that they represented surface rise/fall events associated with migrating pockets of subglacial water. Airborne lidar data flown in the WAIS during the 1997/1998 and 1999/2000 Antarctic field seasons [Spikes *et al.*, 2003] revealed elevation changes of a few meters on a spatial scale of  $\sim 10 \text{ km}$ . For example, results from a KIS flightline (Line L1 in Figure 1) show a 2-year surface height increase of up to 3.5 m at the centre of a  $\sim 10 \text{ km}$  long region. Lidar profiles over the more rapidly moving ice in WIS (Line L2 in Figure 1) showed that one region that was  $\sim 4 \text{ m}$  lower in 1998 than in 2000.

## 2. InSAR Techniques and Results

[4] The Canadian RADARSAT satellite imaged Antarctica during the 30-day Antarctic Mapping Mission (AMM) in 1997 while the radar was oriented to the south [Jezek, 2002]. Satellite radar interferometry (InSAR) requires repeat coverage with the same geometry which is only possible with RADARSAT every 24 days. Most areas in the WAIS were covered by only one image pair, some areas had no repeat coverage at all, but a few areas had coverage by 2 pairs. With only one InSAR pair the ice velocity can be estimated by assuming that the flow vector is parallel to the ice surface and then combining displacements in the line-of-sight direction with less accurate estimates of along-track displacement made using the 'speckle tracking' technique [Gray *et al.*, 2001; Joughin, 2002]. However, for the few areas in the WAIS for which there are both ascending and descending pass pairs it is possible to solve for the 3-dimensional displacements without using the surface-parallel-flow assumption.

[5] RADARSAT imaged area A1 (Figure 1) in a KIS tributary during a descending pass on 24 September 1997, and again in an ascending pass on the 26 September. Both

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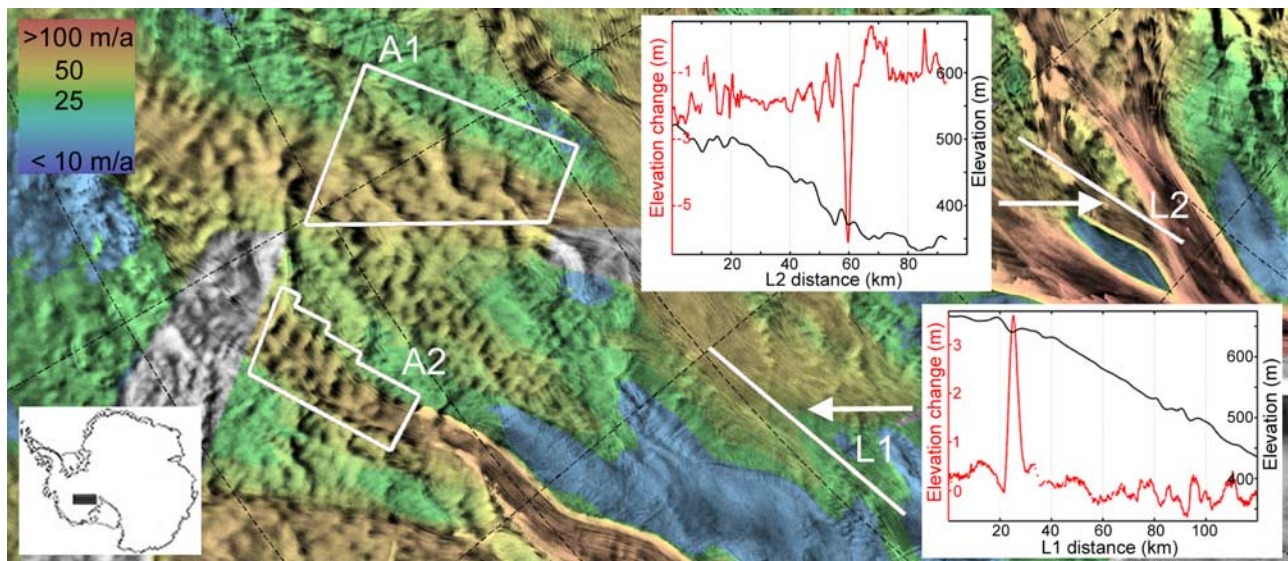
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**Figure 1.** Study areas in the West Antarctic Ice Sheet (WAIS). The background image is from the RADARSAT Antarctic Mapping Mission mosaic, and the color overlay indicates ice speed. Boxes A1 in the tributary of Kamb Ice Stream (KIS) and A2 in the Bindshadler Ice Stream (BIS) outline the areas for which we have a solution for vertical displacement, (Figures 2b and 3b). L1 and L2 indicate the position of the lidar results discussed in the text. The inset graphs illustrate surface elevation (black) and elevation change (red) for lines L1 and L2.

acquisitions were repeated 24 days later to form two temporally overlapping interferometric pairs. A solution for vertical displacement was obtained using the ascending and descending pass InSAR range displacements (from InSAR phase), and the descending pass azimuth (along-track) displacement from speckle tracking. The north, east and vertical displacements can then be derived from the known geometry of the 3 non-orthogonal displacements. Errors in the derived horizontal and vertical displacements are dominated by the error in the smoothed azimuth shift. With a  $2 \times 2$  km smoothing the standard deviation in the 24-day vertical displacement is  $\sim 3$ – $5$  cm. It is hard to constrain absolute errors without more reference velocities, so there is the possibility of slowly changing bias errors of a few cm across Figure 2b.

[6] Ice surface velocity is shown as a colour overlay in Figure 2a, together with the 24-day vertical displacement (Figure 2b). The dark blue area in Figure 2b moved vertically downwards by up to 50 cm during the 24-day repeat cycle. Interferometric phase patterns (inset images in Figure 2b) from the ascending and descending InSAR pairs reflect the line-of-sight range displacement between each pair in the two different orbit geometries. Since the two passes intersect at  $\sim 110^\circ$ , we expect the phase patterns to be quite different except for those variations arising from displacements that subtend the same angle to the two range planes. Vertical displacements satisfy this condition and will lead to the same phase patterns. The depressed area reflected by the common concentric fringe pattern is  $\sim 125$  km<sup>2</sup> in area with a diameter of  $\sim 12$  km.

[7] Vertical surface displacement is also observed in area A2 (Figure 1) upstream of the Bindshadler Ice Stream (BIS, formerly Ice Stream D). In this case the horizontal velocity field (Figure 3a) was interpolated from the move-

ment of GPS reference positions measured in the Austral summers of 1995/1996 and 1996/1997 [Bindshadler *et al.*, 2000]. These data were used to estimate the 24-day horizontal displacements and combined with the radar line-of-sight displacement from an interferometric pair (from Sept. 26 and Oct. 20, 1997) to derive the local vertical displacement (Figure 3b). The red and blue areas (Figure 3b) represent surface uplift and subsidence, respectively.

#### 4. Discussion and Conclusions

[12] The interferometric radar data imply a vertical surface movement of up to  $\sim 2$  cm per day. The lidar data of Spikes *et al.* [2003] also indicate vertical movement that could not be sustained over many years. The results in this paper represent a first indication that these anomalous changes in surface elevation on WAIS ice streams may be linked to subglacial water transport. Further work is required to establish the precise spatial and temporal variation in surface elevation.

[13] Continuing debate about WAIS stability [Alley and Bindshadler, 2001], recent interest in Antarctic subglacial lakes [Priscu *et al.*, 2003], and sediment transport by glaciers [Alley *et al.*, 2003], highlight the need for an improved understanding of the generation, distribution, and flux of subglacial water. Our results suggest that imaging all three components of surface ice displacement in the WAIS will help establish links between basal water transport in the subglacial environment, and ice dynamics and mass transport to the ocean. The RADARSAT 2 satellite to be launched in late 2005, with its flexible geometry and ability to view left or right of track, should help provide such a capability.